An Eight-Meter Inflatable Reflectarray Antenna and Its Inflatable/Self-rigidizable Booms

H. Fang[1], J. Huang[2], U. O. Quijano[3], L. Hsia[4], N. Sorokin[5], and O. Polanco[6]

[1]Houfei Fang; Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109
[2]John Huang; Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109
[3]Ubaldo O Quijano; Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109
[4]Lih-Min Hsia, California State University at Los Angeles, 5151 State University Drive, Los Angeles, CA 90032
[5]Nicholas Sorokin, California State University at Los Angeles, 5151 State University Drive, Los Angeles, CA 90032
[6]Otto Polanco, California State University at Los Angeles, 5151 State University Drive, Los Angeles, CA 90032

Abstract

This paper presents the analysis and test results related to buckling capability, modal characteristics, and thermal expansion coefficient of STR aluminum laminate inflatable/self-rigidizable booms with lengths up to 10 metes. STR booms are fundamental building blocks of space inflatable/self-rigidizable reflectarray antennas. These boom characteristics are essential for analyzing structural integrity, in orbit dynamic response, and in orbit thermal distortion of the 8-mter reflectarray antenna. Distinct advantages of the STR booms will also be identified and presented by this paper.

Introduction

Jet Propulsion Laboratory (JPL), working with selected industry and academic partners, has since the late 1990s been engaging in developing inflatable space radar antennas, including several X-, Ku-, and Ka-band reflectarray antennas [1-6]. Inspired by our recent success in developing a 3-meter Ka-band inflatable reflectarray antenna, space science missions that will employ multiple-band reflectarray antennas with aperture sizes over 8 meters are being considered. Figures 1 shows the deployment process of this reflectarray antenna.

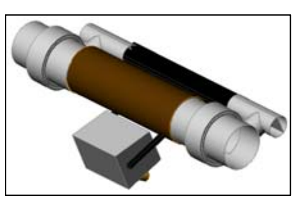

Figure 1a. Packaged antenna

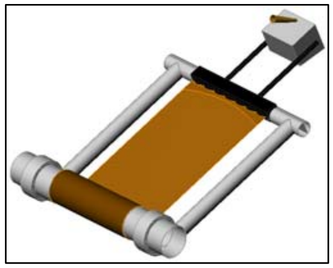

Figure 1b. Two inflatable/self-rigidizable booms and the membrane are unrolling after the feed is turned out of the way

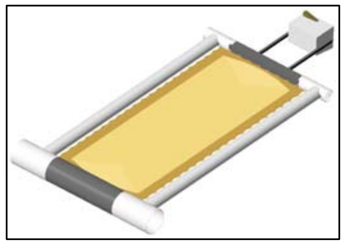

Figure 1c. Two inflatable/self-rigidizable booms are fully inflated

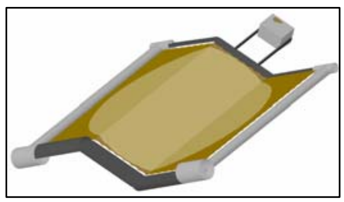

Figure 1d. The membrane and two end-bars are unfolding

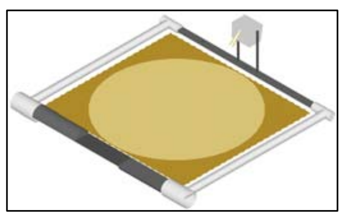

Figure 1e. The feed is turned to the final position and the antenna is fully deployed

It can be seen from these figures that the fundamental structural components for this type of antenna architectures are two Spring Tape Reinforced (STR) aluminum laminate inflatable/self-rigidizable booms. For a reflectarray antenna with an aperture size over 8 meters, the length of these booms will be around 10 meters. Development of inflatable/self-rigidizable booms is an integrated part of our effort for developing the 8-meter multiple-band reflectarray antenna.

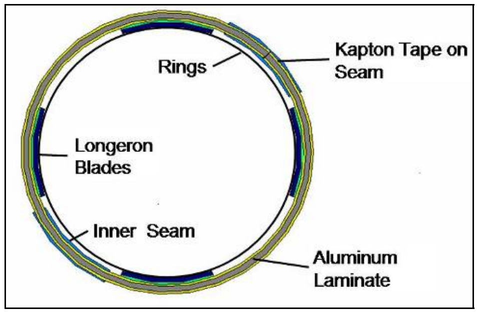

Figure 2a. Cross-section of a typical STR aluminum laminate boom

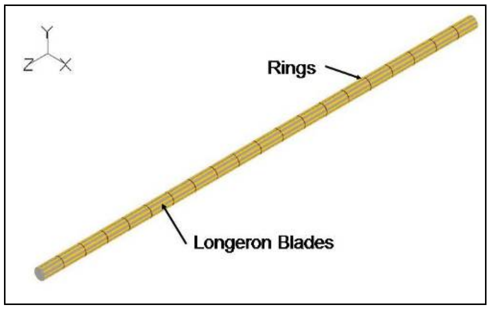

Figure 2b. Isometric view of a 10 meters typical STR aluminum laminate boom

A typical STR boom consists of a tube that is formed with aluminum laminate sheet and seamed by the Kapton tape and two end caps. Figure 2a shows the cross-section and 2b illustrates an isometric view of the aluminum laminate tube. Ten longeron blades are attached to the inside wall of the tube in the axial direction and equally spaced rings manufactured out of spring steel are also attached.

Buckling Test and Analysis

It had been determined by the antenna design analysis that each boom is loaded with 322.5 N (72.5 lb) axial force and the factor of safety should not be less than 3.5. Based on this requirement, axial buckling capabilities of several booms with different diameters were analyzed to determine the baseline design for further developing. The buckling analysis results are shown in table 1. The length of every boom in table 1 is 10-meters. The aluminum laminate of #6 and #7 is 2-mil aluminum with 1-mil polyester on both sides and the other booms are composed of 3-mil aluminum with 1-mil polyester on both sides. Boom # 5 was analyzed to be able to take 2197 N (494 lb) and was identified to be the baseline design.

Table 1. Results of the boom buckling analyses

	Diameter (cm)	# of blades (width)	# of rings (width)	Buckling load (N)
1	16.51	8 (2.54 cm)	18 (2.54 cm)	459.95
2	20.32	8 (2.54 cm)	18 (2.54 cm)	717.50
3	20.32	10 (2.54 cm)	18 (2.54 cm)	753.97
4	24.13	10 (2.54 cm)	18 (2.54 cm)	1253.95
5	24.13	10 (2.54 cm)	39 (1.27 cm)	2197.06
6	24.13	10 (2.54 cm)	18 (2.54 cm)	727.73
7	24.13	10 (2.54 cm)	20 (2.54 cm)	862.07

8	33.02	4 (10.92 cm)	None	1704.11
9	33.02	8 (5.08 cm)	None	1492.38

Three different sample booms of lengths 1-m, 4-m, and 10-m were fabricated to experimentally validate their buckling capabilities (see Figures 3, 4 and 5).

Figure 3. Buckling test of a 1-m boom

Figure 4. Buckling test of a 4-m boom

Figure 5. Buckling and vibration test fixture for a 10-m boom

The sample booms of 24.13 cm (9.5 inch) diameters were fabricated using the 3.81 cm (1.5 inch) curvature spring tapes. The results from the test are tabulated and shown in table 2. Also the graph in figure 6 illustrates the relationship between the load applied and the deflection of the 10 meter long boom.

Table 2. Tabulated results of 24.13 cm (9.5 in) diameter booms

Boom length (meters)	Max. load (N)	Required load capability (N)	Safety factor	Max. load/max. deflection (N/cm)
1	1881.6	322.5	6	735.47
4	1507.95	322.5	4.7	642.96
10 (39 rings)	1757	322.5	5.5	487.65

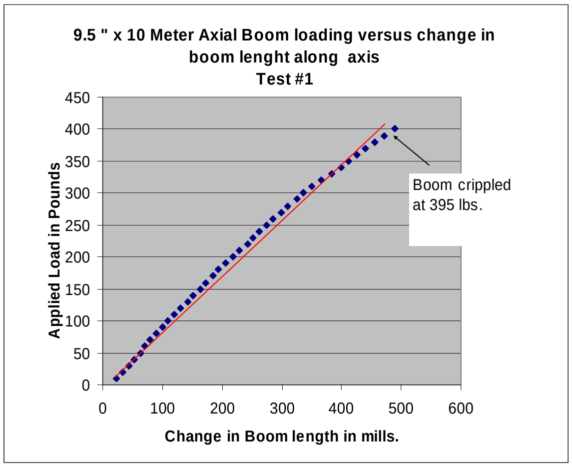

Figure 6. Graph showing applied load versus deflection

Dynamic Characteristics of the 10-meter Boom

The dynamic characteristics of the 24.13 cm (9.5 inch) diameter boom was analyzed and tested. Figure 5 illustrates the testing fixture. The first three frequencies from the analyses and test show good correlation and are presented in table 3. Also, the first two frequency mode shapes are illustrated in figures 7. From the first modal frequency, the equivalent bending stiffness of the 24.13 cm (9.5-inch) diameter boom is calculated by:

$$EI = \left(\frac{\omega_1 L^2}{4.73^2} \right)^2 \rho A$$

Table 3. First three frequencies (Hz)

Frequency number	Test	Analysis
f1	7.41	7.13
f2	20.6	20.8
f3	40.9	41.2

The equivalent bending stiffness of the 24.13 cm (9.5 inch) diameter boom will be used to facilitate the modeling of the entire inflatable space radar antenna.

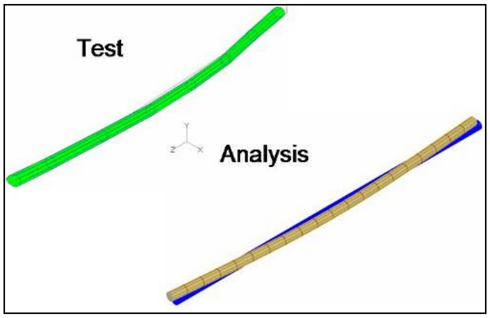

Figure 7a. First mode shape

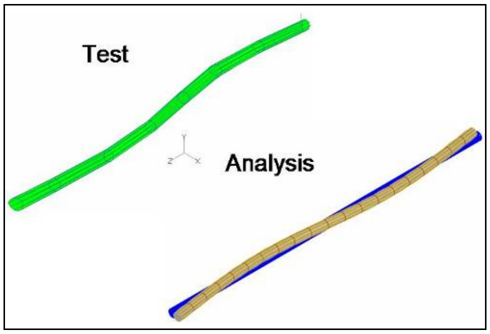

Figure 7b. Second mode shape

Thermal Characteristics

The thermal characteristic of the 24.13 cm (9.5 inches) diameter boom of 0.44-m long was tested using a thermal/vacuum chamber to simulate the harsh space environment. Figure 8 illustrates the set up of the thermal/vacuum chamber test.

Figure 8. Set up of the thermal/vacuum chamber test

The theoretical formula used to compare the experimental value is

$$\Delta L=\alpha(\Delta T)L$$

where α is the coefficient of thermal expansion, ΔT is the differences between initial and final temperature, L is the length of the boom at the initial temperature. The theoretical displacement using steel's CTE is 0.054 cm. The steel's CTE ($11.7 \times 10^{-6}/^{o}C$) was used since the spring tape is dominant compared to the other materials that make up the self-rigidizable boom.

For the actual test, five thermal couples were used to measure the temperature of the boom during the cooling of the thermal/vacuum chamber. The thermal couples were position on the front, center, back, LVDT (transformer) and the copper plate (see figures 9).

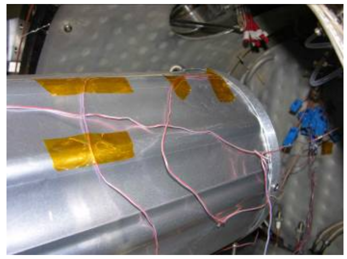

Figure 9a. Position of front and center thermal couples

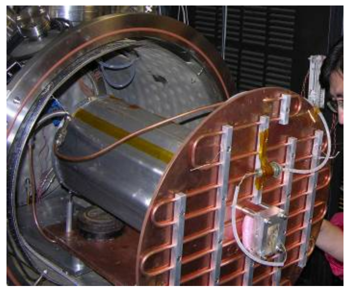

Figure 9b. Position of back, LVDT and plate thermal couples

The data which generated the graph illustrated in figure 10 was obtained from the microprocessor and the controller at the center thermal couple. The displacement went from 0.0107 cm (4.21 mils) to 0.0713 cm (28.08 mils), results a difference of 0.0606 cm (23.87 mils). The experimental coefficient of thermal expansion was calculated by using the following equation:

$$\alpha = \Delta L/((\Delta T)L$$

which yielded a coefficient of thermal expansion of 13.21 x $10^{-6}/^{o}C$. Table 4 shows the comparison of the CTE and displacement of the experimental to theoretical values.

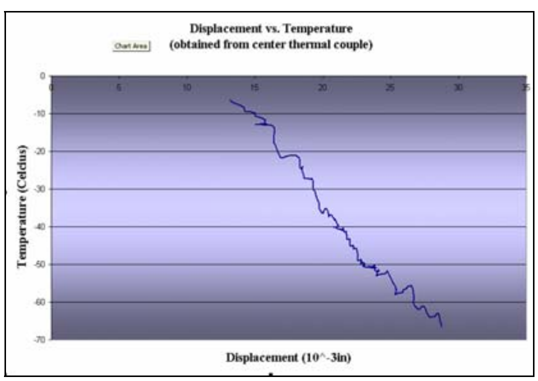

Figure 10. Boom CTE test result

Table 4. Comparison of experimental and theoretical values

	Experimental	Theoretical (steel)
CTE ($10^{-6}/^{o}C$)	13.21	11.7
Displacement (cm)	0.0606	0.054

Conclusion

Through the development process, including design, analysis, fabrication, assembly, and testing, the functionality of the STR boom has been demonstrated and verified. Compare to other space inflatable boom technologies, STR boom has many distinct advantages that include:

- Simplicity of the design
- Self-rigidizable in space
- High load-carrying capability
- High packaging efficiency.
- Requires low inflation deployment pressure.
- Using space qualified materials with negligible out gassing and contamination.
- Reversible for repeated ground testing.

Based on the structural characteristics of the STR boom obtained by this study, structural integrity, in orbit dynamics, and in orbit thermal distortion of the 8-meter reflectarray can be analytically determined during the design stage.

Reference

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